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Literature Review and Preliminary Studies of Fretting and Fretting Fatigue Including Special Applications to Aircraft Joints

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| 16. Abstract This report contains a review of the literature pertinent to fretting and fretting fatigue including special applications to aircraft joints. An introduction is given outlining the importance of fretting and fretting fatigue failures. Proposed mechanisms of fretting and fretting fatigue are then discussed. Research in the literature indicates there are three stages to fretting fatigue life. The first is a period of crack nucleation, usually by adhesion and plastic deformation of contacting asperities in relative motion. Several other possible mechanisms are discussed as well. In the second stage, propagation of nucleated cracks is determined by the stress resulting from the surface tractions imposed by fretting. The results of several investigations of the stress state and its effect on the propagation of nucleated cracks are discussed. The stress state can either dramatically increase early crack propagation rates or retard crack propagation, depending upon the specifics of the contact under study. The third stage is a period of crack propagation during which fretting contact stresses are not significant to crack propagation. Research on possible means to prevent fretting and fretting fatigue is then discussed. It was found that the performance of most methods is highly dependent on the specific application. A palliative which dramatically extends fretting fatigue life in one situation can be detrimental in a different application. Only those methods that increase the unfretted fatigue strength of the material, such as shot peening or phosphatizing, were found to consistently extend fretting fatigue life. Research, specifically on aircraft joints, that could be pertinent to the effect fretting could have on the fatigue life of aircraft joints is discussed. The effect of different palliatives and substances commonly found during an aircraft's service life are also discussed. Evidence that fretting is a possible pervasive mode of failure in aircraft is also given. | | |
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EXECUTIVE SUMMARY

This report contains a review of the literature pertinent to fretting and fretting fatigue including special applications to aircraft joints. An introduction is given outlining the importance of fretting and fretting fatigue failures.

Proposed mechanisms of fretting and fretting fatigue are then discussed. Research in the literature indicates there are three stages to fretting fatigue life. The first is a period of crack nucleation, usually by adhesion and plastic deformation of contacting asperities in relative motion. Several other possible mechanisms are discussed as well. In the second stage, propagation of nucleated cracks is determined by the stress state resulting from the surface tractions imposed by fretting. The results of several investigations of the stress state and its effect on the propagation of nucleated cracks are discussed. This stress state can either dramatically increase early crack propagation rates or retard crack propagation, depending upon the specifics of the contact under study. The third stage is a period of crack propagation during which fretting contact stresses are not significant to crack propagation.

Research on possible means to prevent fretting and fretting fatigue is then discussed. It was found that the performance of most methods is highly dependent on the specific application. A palliative which dramatically extends fretting fatigue life in one situation can be detrimental in a different application. Only those methods that increase the unfretted fatigue strength of the material, such as shot peening or phosphatizing, were found to consistently extend fretting fatigue life.

Research, specifically on aircraft joints, that could be pertinent to the effect fretting could have on the fatigue life of aircraft joints is discussed. The effect of different palliatives and substances commonly found during an aircraft's service life are also discussed. Evidence that fretting is a possible pervasive mode of failure in aircraft is also given.

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1. INTRODUCTION.

The term fretting is often used to describe a phenomenon occurring between two contacting surfaces undergoing low amplitude oscillatory motion. Fretting has been referred to by a number of different terms such as "friction oxidation," "false brinelling," "chafing," "bleeding," and "coca." Fretting Corrosion is a term used to describe deterioration at the interface between contacting surfaces as the result of corrosion and slight oscillatory slip between the two surfaces or a form of fretting wear in which corrosion plays a significant role. Fretting Wear is a term used to describe wear arising as a result of fretting [1].

The use of different terms implies that investigators are not sure of the mechanism/s of fretting. This is because some characteristics of this phenomenon are similar to wear (formation of indentation and scars) and other characteristics are similar to corrosion (oxide formation).

Fretting can act synergistically with other failure modes such as fatigue (fretting fatigue). Fretting fatigue is a term used to describe failure that occurs in contacting structural components in which at least one of them is undergoing a cyclic load. The damaging effect of fretting on fatigue can be illustrated by comparing the data on fatigue life of a component with and without fretting present. Often, these data are obtained from tests where a simple pad is pressed against a surface on a component subject to cyclic load. A reduction in fatigue life is common for fretting. This is because fretting accelerates crack nucleation. Fretting fatigue crack nucleation takes place at several different locations on the contacting surfaces. Some of these cracks can link up in the early stages of crack propagation and create a larger crack. Fretting fatigue cracks propagate in width and in depth under the simultaneous action of fretting and fatigue and thereafter by fatigue only, generally reducing the cross-sectional area of the component to the extent that final fracture finally occurs.

Proposed methods of reducing fretting and fretting fatigue related problems are extensive and involve techniques such as the use of anti-fretting compounds (shims, coatings, adhesives, lubricants, etc.), surface cold working (shot peening, rolling, etc.), and design changes (material, geometry, loading, etc.). Each of the proposed methods has some advantages and some disadvantages. There are also attempts to incorporate fretting into the existing methodology of fracture

mechanics. In any case, due to the complexity of the joints and the many variables involved such as loads, geometry, materials and their behavior, some companies rely on the trial-and-error approach to find the correct solution for a given situation.

The objective of this project was to conduct an extensive literature review from 1960 to mid-1992 in order to identify and assess design approaches, alleviation methods, and mechanisms of fretting and fretting fatigue failure. In this literature review, over 1000 papers were found; their abstracts were copied and are kept in a file in QIDEC*. Approximately 200 of the most relevant papers were copied entirely and are kept in the file.

The organization of this report is as follows: The next section discusses mechanisms of fretting and fretting fatigue which include damage production and growth as well as crack nucleation and propagation. A section of this report is devoted to the mechanisms of fretting and fretting fatigue in joints in general and aircraft joints in particular. Then different approaches to reducing or preventing fretting and fretting fatigue are discussed. Another section then covers work in the literature which is specifically applicable to fretting and fretting fatigue of joints. The last section is devoted to summary remarks and conclusions.

* QIDEC- Quality and Integrity Design Engineering Center at the University of Utah.

2. MECHANISMS OF FRETTING AND FRETTING FATIGUE.

2.1 THE CURRENT STATE OF KNOWLEDGE ON FRETTING AND FRETTING FATIGUE MECHANISMS.

Being able to predict fretting and fretting fatigue failures accurately for a random situation is presently beyond our capability. This is due to the large number of parameters which can affect fretting and the complex interactions among them [2,3,4]. There is, however, a growing agreement on the general mechanism by which fretting reduces the fatigue strength of metals.

2.2 FRETTING WEAR AND FRETTING CORROSION.

The literature often separates fretting wear into two distinct stages. The first is a period of high wear rate due to initial adhesion, plastic deformation, metal transfer, and smearing of surfaces [3,5]. The second stage is a period of debris build-up as deforming surfaces oxidize and rupture, followed by further oxidation and pulverization [6,5,3].

2.2.1 Adhesion, Metal Transfer, and Plastic Deformation.

The first stage of fretting is evident by an increase in the coefficient of friction [7,8,5]. The coefficient of friction can increase from 0.2 to 0.55 within 20 cycles [7].

It has been shown that high coefficients of friction are a function of the reduction in free energy when surfaces contact (W_{ab}) and hardness of the surfaces (h). High frictional coefficients result from high W_{ab}/h ratios and thus are related to increased adhesion [5].

Tomlinson was the first to suspect the increase in coefficient of friction was due to what he called "molecular attrition", or adhesion [5]. A commonly accepted view is that a thin oxide layer and/or surface films are initially wiped or abraded away [8,5]. Asperities on opposing surfaces contact and form intermetallic joints by adhesion [5,4,2,3]. Reports suggest this process may reach a maximum from around 20 to 5000 cycles [2,5]. These adhesive contacts are very important as they are often thought to be the mechanism by which the majority of cracks are nucleated. They are also thought to determine how much wear occurs during later processes [5].

When adhesive contacts are made there is significant plastic deformation. Actual contact area is small and stresses are high [6]. Buckley has reported seeing slip bands behind a frictional contact, a sign of plastic deformation. He also reports having seen fractures in the same area. This effect has been attributed to high tensile stresses behind the contact [8]. This is consistent with observations of cracks usually nucleating at the edge of microscopic contacts. Cracks may also form on top of asperities but subsequently are worn away [9]. The angle of micro-cracks has been observed to form at 45 degrees to the sliding direction where the plane of maximum shear stress would be expected [6].

After the initial period of rapid increase in coefficient of friction, there is an incubation period. During this period of plastic deformation the coefficient of friction remains relatively constant.

One author has suggested that adhesive contacts be put into three categories [2]. The first occurs when wearing surfaces are separated by a thick third body (a film). Normal and shear loads are transmitted across the third body. Friction is low and no cracks develop. The second type has a small contact area in which there are no third bodies. Adhesion and friction are high. Short cracks, less than 50 micrometers, may form on either side of the contact. The third category has a large contact area with no third bodies. Adhesion and friction also are high. Long cracks, greater than 500 micrometers, can develop on either side of the contact [2].

The common observation that increased amplitudes increase wear rates also may be attributed to adhesive contact. When a crack forms it locally relieves the stress around it [3]. The stress due to asperities contacting is a local effect which is only significant to about the distance between asperities [9]. This suggests that as the amplitude is increased, a contacting asperity can move outside of the relieved stress area from a previously nucleated crack and nucleate another.

Gouges in both surfaces also may appear during this stage. This is the result of contact between asperities and instead of bonding, they gouge into one another [5].

2.2.2 Oxide Build-Up and Steady State Three Body.

The second stage of fretting wear occurs as oxidized debris particles build-up. They can come from several sources and may have a dramatic effect on fretting wear and the contact stress state. Particle detachment can start as early as the first few cycles [10].

After the adhesive contact of asperities, several things can occur. Once a junction has formed, plastic deformation and strain hardening strengthen the area near the original contact [2]. If the new junction is weak enough, the asperities may simply separate at the same location where they joined. If the contact is strong, the junction may break in a location other than where the asperities first joined, and metal would transfer from one surface to another [9,5,2]. Metal usually transfers to the harder surface [11]. This process exposes active metal at two locations, at the surface which lost the asperity and at the piece of transferred metal. Free surfaces and internal discontinuities support adsorption of gaseous oxygen, which then dissociates and oxidizes the metal [5]. The piece of transferred metal would oxidize and may break off to form a partially oxidized third body particle [9]. One study suggested only 0.01 percent to 5 percent of junctions result in the formation of a particle. It has been suggested this process may be thought of as incomplete metal transfer. Oxidation occurs before transfer is complete and abrasive particles are formed [5]. If the rate of deformation is greater than the rate of oxidation then the surface would become smeared [4,11]. Pits are also formed by adhesive contact [9].

A similar theory of particle formation suggests that when enough transferred metal particles with some oxide are embedded into the base metal it is difficult to determine a true metal/oxide debris boundary [5,12]. The thin oxide in the transferred material makes the zones of transferred material weaker. The zone eventually does not transfer material but the motion dislodges wear particles [5].

Another theory is supported by the observation that debris particles are often thin plate-like sheets [13,14,15]. The theory of delamination is often used to explain this. It suggests that material near the surface is cold worked less than the subsurface layer (dislocations are eliminated at the surface by the 'image force' a result of the stress-free surface). A pile-up of dislocations will occur a finite distance from the surface. Voids will form and then coalesce. Cracks are formed because of the low "ductility" [13,14]. One author

suggests that cracks may form at the surface, then propagate parallel to the surface, or, the cracks may form subsurface and propagate parallel to the surface [14,9]. At a critical crack length the material from the edges of the crack to the surface will shear [13,14]. When these cracks propagate towards the surface rather than into the material, large plate-like particles can be produced [3,9,4,11]. One source suggests these particles could not be formed by metal transfer as fractographic observations show the top surfaces have characteristic wear grooves. If they were metal transfer particles the grooves would be on the opposite side [14]. These particles are then ground into finer particles [4].

Some sources do not consider abrasion to be the mechanism of wear, as damage to the surfaces occurs even when the surface is harder than the debris. Also, there is disagreement in the literature as to whether wear rates increase or decrease after debris is built up [5,3,6]. It might be that wear rates can either increase or decrease depending upon amplitude and particle size. Oxidized or work-hardened unoxidized particles may be capable of abrasive wear mechanisms and the surface may be gouged and/or worn [5].

As fretting continues, the oxidizing particles break up and distribute [6,5]. This alters the fretting conditions as surfaces start rolling on debris and/or the debris settles to distribute stresses more evenly. The surfaces may even be completely separated with debris, decreasing the coefficient of friction [6,2,5,4]. Rolling debris can also work harden the surfaces and increase resistance to fatigue damage [6]. Some investigators suggest the combined effect of the debris is great enough that both wear and subsurface protection are dependent on the effects of debris [2]. The lubricating properties of the particle layer are highly emphasized by some investigators [11,10]. Some suggest that fretting fatigue damage is determined by whether the protective debris layer can form before a crack can nucleate and propagate [10]. One investigation has found that artificially introduced third bodies (such as powdered oxides) offer just as much protection as naturally produced debris [2]. Except when third bodies are very abrasive, wear rates will increase if third bodies are periodically removed [10].

It has been observed that both the chemical consistency of the debris and the amount of debris can vary over the fretting area [5,3]. Godfrey fretted a ferrous material and found that the color was black in the center and got red-brown closer to the edge. It was postulated

that this was due to the increased availability of oxygen near the edge [5]. In another study, debris location was found to change with slip amplitude. Debris remained in the contact area at low amplitudes. For high amplitudes, debris collected in a ring around the edge of contact. The author suggested this may be why higher amplitudes increase wear rates. As debris leaves the center of contact, contact stresses are less distributed and surface to surface contact may be possible [3].

There is considerable controversy in the literature over the temperature rise during fretting. Observed metallurgical transformations, such as the white etching layer, often have been used as evidence for increased temperatures [10,16]. This is in disagreement with experimental and theoretical work suggesting that not enough power is lost to friction to significantly increase temperature. Pure rolling also has been found to produce a material similar to the white etching layer. With steels, this layer may be due to cold work producing a fine grained ferritic structure [10].

2.3 FRETTING FATIGUE CRACK NUCLEATION.

Determining exactly what mechanisms are at work during fretting fatigue has been difficult, as many conditions are present which could result in the formation and propagation of a crack. Cracks can nucleate during fretting by several possible mechanisms. The more commonly proposed are low cycle failure due to adhesively contacting asperities, the stress concentration of a geometric gouge from abrasion, delamination, pits, or the macroscopic increase in stress due to contact [6,3,17]. Other possibilities include the rupture of surface films with subsequent exposure to the environment, or an accumulation of discontinuities that reduce fracture energy [9]. Investigators have sorted through the effects of increased stress due to contact, fretting wear damage, environment, etc. and have determined that most fretting fatigue failures are not the result of a single variable, but a combination. While there is disagreement as to the relative importance of each effect, most current theories view the mechanism of fretting fatigue as occurring in four stages. First, the crack nucleates from wear damage. Then, due to contact stresses there is a period of crack propagation that is faster than would be attributable to bulk stress alone. Once the crack has grown beyond the influence of the contact stress state, the bulk stress alone can result in crack propagation. Fast fracture may eventually occur as

the crack grows. Environmental effects could possibly make a significant contribution at each stage.

Many investigators use Mode I stress intensity factors during both early and final crack propagation. The validity of doing this has been seriously questioned. Many believe Mode II stress intensity factors should be included. Also, since it is a generally accepted fact that early crack propagation does not proceed normal to the surface, there is little doubt that using stress intensity factors based upon a perpendicular crack will be in error [18,19].

Studies on the effect which fretting slip amplitude has on fatigue life must be carefully scrutinized. Fretting usually involves slip amplitudes of less than 25 micrometers, with no minimum slip amplitude [20,10,15]. If the slip amplitude is larger than this and over the entire area of contact, it is usually called reciprocating wear. Wear rates increase and wear can be predicted by the common equations relating wear rate to distance traveled and normal load [15,11]. There are several sources of error which are quite large in comparison to slip amplitudes characteristic of fretting and could invalidate many findings. Possible sources of error include elastic displacement of the test machinery, elastic displacement of the cracked specimen, and plastic 'card slip' deformation of the specimen. A propagating crack can also allow relative motion that might be misinterpreted as slip. One author suggests that constant amplitude tests are extremely difficult if the coefficient of friction varies [10].

One investigator has found that a critical fretting amplitude exists below which wear rates drop drastically [13]. Other investigators found a greater reduction in fatigue life as amplitude was increased [21,22]. One author suggests that for elastic slip fatigue strength is decreased by increasing slip amplitude and for macro-slip, where friction force is independent of slip, fatigue strength either increases or stays constant as slip amplitude is increased [22].

The effect of frequency on fretting is also difficult to determine. Increasing frequency may either increase, decrease, or not change fretting and fretting fatigue. Possible parameters dependent upon frequency are corrosion rates, resonance affecting third body movement, and temperature [10,23].

2.3.1 The Damage Threshold.

An important step in discovering the mechanism(s) of fretting fatigue is determining when fretting has an effect on fatigue life. It then is possible to concentrate investigations on what processes occur during that period of fretting.

It has been suggested that fretting decreases fatigue life by creating an initial "flaw" or crack very early [17]. Tests were conducted during which the fretting pads were removed at different periods during the life of specimens [24]. The results showed that after a certain amount of fretting damage, contact had no further effect on life [25,3,12]. The tests also showed that a fatigue life reduction occurred only after a specific amount of fretting damage [24]. These two events appear to occur close to one another during the life of a specimen. The number of cycles at which these events occur is called the damage threshold. The damage threshold is thought to be the point at which a crack has nucleated and has begun propagating [25]. Thus, the 'damage threshold' is dependent not only on the nucleation stage of fretting but also on the contact stress state. The stress state determines how large a nucleated crack has to be in order to propagate.

This view is supported by observations of cracks nucleating in aluminum after only a few thousand cycles when the cycles to failure is 10,000,000 cycles [4]. One author suggests that the average lifetime taken in nucleation and the slow growth cycle is about 10 percent of life [4]. Another study showed that after 25 percent of life, crack growth was independent of fretting or friction [26]. A contradictory view holds that fretting fatigue is a nucleation-controlled process and that even in fretting fatigue, the majority of life occurs during nucleation [7].

2.3.2 Role of Oxidation.

Fretting experiments where oxidation was impossible have shown that oxidation is not required for fretting wear or fretting fatigue [5,3,25,9]. Investigators have used materials which do not oxidize (gold, platinum, cupric oxide, and glass) and placed active materials in a vacuum or inert environment [5,3,25,9,15].

Several investigators have found that in an oxidizing environment there is an increase in cycles to failure as frequency is increased

[25,3]. This suggests that while environmental effects are not required, they could make a significant contribution to fretting fatigue. The role of oxidation is also apparent from the effect of humidity which is known to significantly affect corrosion rates. One study of joints found that fatigue life was related to humidity. Other reports contradict this finding [27]. One study suggested that the chemical contribution to fretting fatigue may be more important than the mechanical contribution. It was found that for 7075-T6, the fretting fatigue lives were 10 to 15 times longer in a vacuum than in air [3]. Uhlig suggests fretting is due to both mechanical and chemical means. He suggests asperities interact mechanically and expose active metal. The exposed metal would then oxidize [5]. Waterhouse suggests that without oxygen, fretting action is similar to uni-directional wear and is purely mechanical. When oxygen is present he suggests the chemical action dominates [5,28].

The differences in theories on fretting fatigue are often related to when and how oxidation affects fretting. However, proponents of different theories often only debate on the relative influence of each mechanism [5].

There is reason to believe that oxidation during fretting may proceed differently than in a static situation. When sliding occurs there is plastic deformation. Plastic deformation can significantly increase chemical or diffusion processes. The dislocation movement results in preferential chemical sites of high energy. Layers with absorbed or chemisorbed elements can also have a low shear strength [5].

For some materials the environment can affect the mechanism of fretting fatigue due to the differences in corrosion products. For example, titanium is more sensitive to the type of corrosion product than low carbon steel [25].

The build-up and oxidation of particles during the second stage of wear can have a dramatic effect on fretting fatigue. One source states that since pulverized debris has been known to protect surfaces, the rate the formation of third bodies between fretting surfaces may govern their fretting wear and fretting fatigue properties [2].

It is suggested that another effect of debris is to abrade away nucleated cracks before they can propagate [4]. Debris may also affect fatigue performance if it gets into propagating cracks [17].

As fretting continues particles continue to oxidize. Corrosion fatigue may also become important and is suspected as being the cause of high cycle fretting fatigue [6].

2.3.3 Adhesive Wear Based Mechanisms of Fretting Fatigue Crack Nucleation.

Theories on the mechanism of fretting fatigue often center around the nucleation of a crack from the resulting wear damage of fretting [25]. Damage that occurs during the adhesive wear stage is often thought to have the most deleterious effect because so many damage sites are produced. From fractography it was found that the rate of growth of fretting fatigue cracks during the first stage of wear was 1,000 to 10,000 times the rate for fatigue with no fretting [6].

Poon and Hoeppner [29] found that mechanical damage, not chemical corrosion, plays an important role in fretting fatigue life reduction. Poon and Hoeppner [30] also found that both adhesion and abrasion contribute to the fretting fatigue process by producing wear debris and fretting damage. Additionally, they believe that growth of fretting damage leads to the nucleation of a mode I crack.

One author found that three events occur at about the same order of magnitude of cycles. These are the fretting fatigue damage threshold, the incubation period of wear (explained in 2.2.1), and the fatigue of metals loaded near their yield point. The author suggests that low cycle fatigue at the scale of asperities may be the cause of the rapid increase in wear and fatigue failures. The author warns that since fretting wear can decrease in an inert environment, other factors are also involved [3].

An author has observed that even with unidirectional sliding, surface cracks can be formed [3]. The same author reported fracture along slip-bands at the trailing edge of a contact area [3,8]. The author suggested these cracks were the result of adhesive forces forming tensile stress at the surface [3].

In another study the author compared experimental fretting data with the stress state predicted by a finite element model. When lives were long, the value of the stress concentration from the finite element model was not high enough to be the sole cause of failure. The author assumed that something more than the stress state must be the cause of the reduction. Although the magnitude of the stress

was not high enough to predict the fatigue strength, the coupon broke at the predicted location of maximum stress [8]. This suggests that the crack could not have been nucleated by the stress state alone, but that it could have been aided by the stress state.

A phenomenon known as the 'size effect' is another indication that wear processes are significant to fretting. The theory suggests that the real area of contact has an effect on fatigue life [7]. A series of tests were conducted with fretting pads of different contact areas [8,7]. The investigators found that as contact area was decreased, there was a specific area below which fatigue life was infinite [8,7]. The authors suggest this effect is due to the requirement of a certain real contact area between asperities to nucleate a crack. It is improbable that this effect could be attributed to a lack of surface damage as it has been shown that slip amplitudes as low as 0.025 micrometers can induce fretting damage [3].

One source suggests that fretting fatigue cracks also can nucleate at pits [9]. These pits can be formed by the adhesive contact of asperities, by corrosive processes, or by oxides [9,12]. Some investigators found small pits in an area of low contact pressure. They tried to experimentally determine if these pits could act as crack nucleators by indenting a coupon surface with a micro Vickers hardness tester. The sharp indentation, even though it was work hardened, was a high stress raiser. The specimens were cycled in fatigue with a fretting pad over the indentations. No cracks originated from the pits, but a crack at the surface was observed. This suggests pits are not a primary crack nucleator. However, large pits can be found at the center of fretting wear, but only rarely. Fatigue cracks have been observed at the bottom of these large pits [31].

Other investigators attempted to determine if pit digging or asperity contact was the usual mechanism of crack nucleation. They suggested that abrasive pit digging would produce pits elongated in the direction of sliding. This would mean that abrasive pits would have a lower fatigue strength if cyclically stressed 90 degrees to the direction of fretting sliding. Cracks formed by asperity adhesive contact would behave just the opposite. Adhesive contact would tend to nucleate cracks perpendicular to the direction of fretting sliding so that the lowest fatigue lives would occur when the direction of fretting sliding was parallel to the direction of applied loading for plain fatigue. It was found that the direction of fretting

motion relative to the cyclic plain fatigue load has a dramatic effect. The results of this study indicated that asperity adhesive contact is the dominant mechanism of fatigue crack nucleation [32].

2.3.4 Other Mechanisms of Fretting Fatigue Crack Nucleation.

During any stage the surfaces can be gouged by contacting asperities, oxidized debris embedded in a surface, or free debris between the surfaces [5]. These gouges may act as stress concentrations. Under the increased stress due to contact, a crack could nucleate simply due to the gouge acting as a notch [6].

It has been proposed that the reduction in fatigue strength under fretting conditions may be solely attributed to the contact stress state (a detailed explanation is given in the palliatives section). However, the majority of evidence suggests this is not true for most fretting situations.

Suh [33] introduced the delamination theory in order to explain the mechanisms of crack nucleation and propagation in sliding wear. This theory was later adopted by authors including Gaul et. al. [34] and Waterhouse [35] to explain fretting nucleated fatigue. This theory is based on dislocation movements on the surface and subsurface. Waterhouse suggested that the subsurface cracks formed by delamination were not propagating under the cyclic fatigue loads. Some fretting data suggests that cracks nucleate before the delamination has begun [4]. Until more reliable evidence for these models is found they must be placed in the category of unverified hypotheses.

2.4 EARLY PROPAGATION OF FRETTING FATIGUE CRACK BY STRESS STATE.

Several stress intensity solutions have been developed to allow a fracture mechanics prediction of crack propagation. An author suggests the stress intensity factor at a fretting pad has three components, the bulk stress, the frictional stress, and the pad pressure [26]. If the nucleated crack size cannot be estimated from the previous section on nucleation, one source suggests assuming an initial crack size equivalent to the depth of the plastically deformed layer (1 to 100 micrometers). The thickness of this layer is dependent on hardness, pad pressure, and asperity geometry [9,2].

Many conditions occur during practical fretting situations which can develop extremely high local stresses [36]. A classical example is the work of Hertz and Mindlin. Their analysis has shown that when a sphere contacts a plane, and a force is applied tangent to the surface, the shear stress in the annular region at the edge of contact will approach infinity [16,37]. Obviously the stress cannot reach infinity and slip will occur to relieve the stress. These stresses result from the opposing shear stresses. One surface tries to expand or contract more than the other.

Another possible large local stress occurs when one surface ends abruptly and acts as a hard point. There is a reduction in this effect when pad pressures are low and large amounts of slip are allowed to occur [8].

A high local stress also results from push-pull or bending contacts [8]. If two flat surfaces contact, one having much less area than the other, a bending moment at the contact will result from pulling on one of the surfaces or applying a bending moment. The smaller contact will deflect under the bending moment and dig into the opposite surface at one end. The surface at the other end of the pad will lift from the surface [8].

The above examples illustrate that at times slip can be very beneficial as it significantly reduces stress levels [8]. Slip also absorbs energy and is a source of damping. However, increasing slip also allows increased wear by adhesion and crack nucleation (see nucleation section).

Possibly the most damaging stress from contact is the tensile stress approximately tangent to the surface just behind a contact. If a force is applied tangent to two surfaces in contact, a large compressive stress will occur at the front of the contact and a large tensile stress behind the contact [8,16,9]. These stresses result for an entire fretting pad or for microscopic contacting asperities. The volume of material at high tensile stresses behind a contact increases very rapidly as the coefficient of friction is increased. The depth to which high tensile stresses occur may be critical. A nucleated crack may need this tensile stress to grow large enough so as to propagate by the bulk stress alone [8].

Many cracks have been observed in areas of fretting which do not propagate past about a 50 micrometer length [38,31,39,18]. One

author suggests there is a fretting fatigue limit below which a crack nucleated by fretting will not propagate [40]. This concept is based on a threshold stress intensity factor required to propagate the main fatigue crack [38]. This limit may occur only for constant amplitude tests.

The mechanism responsible for many fretting nucleated cracks not growing past a certain length is probably due to the frictional stresses. The tensile stress parallel to the surface becomes compressive below the surface and will tend to close a crack. The crack may not be able to grow past this zone of compression and will remain less than a millimeter long. If the bulk stress is larger than this compressive stress, then the crack will grow. Thus, increasing pad pressures may both nucleate cracks sooner and prevent their early propagation with these compressive stresses. However, both before and after the depth at which this compressive stress exists, a nucleated crack will grow faster than it would under just the fatigue loading [11].

The compressive stress that exists at some level below the surface also can be used to explain the experimental behavior of fretting fatigue specimens with a mean fatigue stress. A mean tensile stress, up to a point, will decrease the fatigue life. Mean tensile stresses compensate for the compressive stress set up below the surface by the frictional force. After there is enough mean tensile stress to keep a tensile stress on the crack over the duration of the alternating stress, additional mean tensile stress will not further decrease the fatigue life [11,39]. Thus mean compressive stresses can prevent propagation but not nucleation [39]. A mean compressive stress slows crack growth but cracks may propagate even under a mean compressive stress if debris gets into the crack and wedges it open [11,39].

The preceding information applies when fretting and fatigue occurs at the same time. There is an interesting result if a specimen is fretting under a mean stress, then cycled in fatigue. Investigators have observed that if a compressive stress is put on the specimen while it is fretted and then it is cycled in fatigue, fatigue lives are greatly reduced. The opposite is true for applying a mean tensile stress. Apparently when the mean compressive stress is released, it allows any cracks nucleated to open further [39].

During initial growth, cracks tend to grow at a slant, so as to go under the fretting pad [4,26]. This effect often results in a tongue protruding from a fracture surface [4]. During initial propagation cracks usually grow inclined to the fretting surface. After they reach a certain length, cracks often change direction and proceed at 90 degrees to the surface [40,38,18,12]. The location of crack nucleation and its direction early in life can be explained from an analysis of the elastic strain energy produced by the fretting pads. Fatigue cracks will propagate in the direction which results in the least strain energy [40].

When a fretting test uses a 'bridge' contact, the nucleated cracks which do propagate to failure are usually at the outside edge of contacts. They propagate faster on the edge because the stress intensity is highest at the ends of the fretting scar than under the fretting scar. This is because all surface frictional forces are pulling at the crack in the same direction. It is the cracks which are on the 'outside' edge that propagate to failure because the stresses at the inside edge of the pad tend to cancel one another out. When the friction force results in a compressive stress, the bulk stress is tensile and visa-versa [41].

The stress state for many idealized situations already has been determined. The usual method is to determine the stress state from surface tractions parallel to the surface and normal to the surface separately, then combine the result with the bulk fatigue stress [42,40,37]. Their usefulness is very limited in practical situations as even slight changes from the idealized situations can drastically alter the stress state. The only reasonably accurate method of determining the stress state in a specific fretting application is to create a finite element model and attempt to account for changes in coefficient of friction, amplitude, etc. during the life of the component.

A new method of analyzing the fretting stress state has been proposed. It is based upon 'stress singularity parameters'. The proponents of the theory suggest that adhesive and fretting strengths based upon maximum stress are not valid as stress and displacement fields show singularity [43].

2.5 FINAL PROPAGATION OF FRETTING FATIGUE CRACK BY STANDARD FRACTURE MECHANICS.

Since the contact stress state changes with depth into the fretting specimen, a crack depth can be reached at which the contact stress state is insignificant in comparison to the bulk alternating stress [18]. At this point the effect of the fretting pads can be ignored and only the bulk alternating stress and perhaps the constant pad pressure need be considered.

It was not until the late 1970's that investigators began to study fretting fatigue by modeling it with the aid of linear elastic fracture mechanics (LEFM). The first investigation on the subject was conducted by Edwards, Ryman, and Cook [92] who introduced a fracture mechanics technique that could predict the life span of a specimen undergoing fatigue and fretting simultaneously. The model they constructed used the stress intensity factor (K) equations derived specifically for fretting fatigue by Rook and Jones [93]. In this model predicting the fretting fatigue failure, Edwards, Ryman, and Cook [92] assumed failure would occur when the maximum stress intensity factor exceeded the fracture toughness of the specimen material. Rook and Jones derived the stress intensity factor (K) equations by assuming a simple two-dimensional model of straight-through edge-crack in a sheet subjected to localized forces. Even though Rook and Jones derived the stress intensity factor (K) for both mode I and mode II, Edwards et al. did not take the mode II stress intensity factor into account in their own model. They limited the input parameters, which contributed to the mode I stress intensity factor in their model, to the following three: body stresses due to externally applied loads; alternating frictional loads; and normal pad loads. This model was applied to aluminum alloy specimens with steel fretting pads under constant and variable amplitude loading [94] and, as the authors commented, "the accuracy of the predictions was good considering the possible source of error."

After Edwards et al. presented their model, other investigators also attempted to develop a fracture mechanics model of fretting fatigue. In 1985, Nix and Lindley [95] developed a similar fracture mechanics model. This model enables any interested parties to calculate the critical crack size for fatigue crack growth under fretting conditions. When applied to aluminum alloy 2014A-T6 specimens in contact with steel fretting pads, their models showed a good agreement between the calculated critical crack sizes and the actual maximum

depth of crack observed by metallographic sectioning through a fretting scar. In the same year, Hattori, Nakamura, and Watanabe [96] proposed another model which obtained the fretting fatigue limit by comparing the threshold stress intensity factor range, $K_{I\text{th}}$, with the actual stress intensity range at the crack tip. In order to achieve this task, Hattori et al. used the Rooke-Jones [93] stress intensity factor (K) equations. They also employed a finite element program to analyze the input parameters for the model, which are contact pressure and tangential stress distributions.

3. REDUCTION OR PREVENTION METHODS.

The only way to completely eliminate fretting is to prevent the fretting surfaces from contacting, or to prevent all relative motion of the surfaces [44]. All relative motion can be stopped by either making the product from one solid piece, thus eliminating the joint, or permanently bonding the two contacting pieces by welding or with a strong adhesive [45]. These options often are not attractive due to increased initial cost, increased cost of repair, and increased difficulty of disassembly. Also, awareness of fretting problems often does not surface until much of the design has been set, and then the only possibility may be the use of a palliative [16,44]. Usually, like fatigue, the best one can hope for is to reduce the effects of fretting [46,44].

The behavior of a palliative is highly dependent on the specific application [9,47]. Reducing fretting and fretting fatigue is often a trial and error process. For example, fretting damage can sometimes be reduced by increasing normal pressure if this significantly decreases relative motion. If the pressure is increased and motion is not substantially reduced, then fretting damage will increase [9]. Also, a palliative that reduces one specific type of fretting damage will not necessarily be beneficial for another type. A good example would be hard metal coatings. They may effectively reduce fretting wear and still have reduced fretting fatigue lives due to decreased unfretted fatigue strength.

The only palliatives that are predictable in untried situations are those which work by increasing the unfretted fatigue strength. Shot peening, sulphidizing, and phosphatizing are the only palliatives that have been shown to be reliable in a variety of situations [47,37]. By the same argument, it is usually advisable to avoid anything that would decrease the unfretted fatigue strength [45].

Based upon some mechanisms proposed earlier for fretting fatigue, the following are basic guidelines to follow in reducing fretting fatigue:

1. Alter the geometry of the contacting surfaces to minimize the stress concentration due to surface shear stresses.
2. Modify the surface with a palliative to obtain the optimal coefficient of friction. At times it may be desirable to have increased friction, at other times it may be best to decrease friction.
3. Select a palliative which minimizes the amount of fretting wear and damage to the surface. This includes reducing adhesive attraction between asperities. Asperity welds can result in microscopic stress concentrations sufficient to nucleate cracks. Also, anything which interferes with mechanisms that result in abrasion may be beneficial. Sites of damage are sites of stress concentration.
4. Do anything that increases the unfretted fatigue strength without adverse side effects. An example would be surface residual compressive stress.

3.1 STRESS VIEW OF PALLIATIVE BEHAVIOR.

Much confusion exists in the literature over the effectiveness of different methods used to reduce fretting fatigue. Investigators working with the same palliative, but applying them in different situations, report much different findings. Although some palliative behavior could be explained by the effect they had on the unfretted fatigue strength most behavior could not be explained. Several investigators have suggested that much of the disagreement in the literature may simply be the result of a palliative's effect on the stress state. They suggest that in some situations it is beneficial to have an increased coefficient of friction, and in others it is beneficial to have a decreased coefficient of friction. They also suggest a method to determine what the desirable coefficient of friction is in a given situation.

Some of the first investigators to expand the theoretical basis were Nishioka and Hirakawa. Their experiments showed a linear decrease of fretting fatigue strength with increasing pressure, based on the

nucleation of cracks. When fretting fatigue strength was based on fracture, it decreased only gradually as pressure was increased, eventually reaching a critical pressure. The authors considered this behavior as being due to stress concentration of the fretting surface stresses. They compared this effect to the behavior of notched specimens in fatigue [48]. They suggested that the main contributor to fretting reducing the fatigue strength is due to the stresses resulting from the alternating friction force. Cornelius and Bollenrath, Thum, and Peterson have all found an indirect linear relationship between fretting fatigue strength and contact pressure [48]. Nishioka and Hirakawa showed good agreement between their experimental results and the stress explanation for fretting behavior [37]. Nishioka and Hirakawa recommended that in order to improve fretting fatigue strength either the contact pressure must be reduced or the relative motion should be constrained (increase contact pressure or coefficient of friction). If a palliative is not used, only one of these solutions can be selected [48].

Gordelier and Chivers expanded on Nishioka and Hirakawa's theory. Their experience has been that practical fretting fatigue failures have very little fretting wear at crack nucleation sites [37]. They consider fretting fatigue to be the result of surface and near-surface stresses. They assume that slip at the interface is not a dominant variable [49]. They suggest the behavior of a palliative strongly depends on the stress field that results from contact and movement [47]. In order to attempt to predict palliative behavior, they derived the stress states for a sphere or cylinder on a plane. Full slip and partial slip cases were considered [37].

They are also advocates of a method of categorizing fretting conditions by what controls motion. A force controlled condition occurs when the force is given and relative displacement is a dependent variable. A displacement controlled condition occurs when the displacement is given and the reacting force is a dependent variable. Gordelier and Chivers acknowledge that most practical cases of fretting are somewhere between purely force controlled and purely displacement controlled. They suggest that the determination of just where a given practical situation falls between these two pure extremes is an important part of predicting behavior and admit it is difficult to judge [37].

Beard also suggested that the view of fretting fatigue be changed from being created by fretting wear, to being created by the stress

distribution resulting from contact. He suggested a rule-of-thumb for selecting a palliative and conditions at the fretting surfaces based upon force-displacement controlled categorizing. For force controlled fretting situations the normal load and friction coefficient should be increased. This lowers slip and thus wear rate. For amplitude-controlled fretting situations the normal load and friction coefficient should be decreased. This reduces contact stress levels. Beard didn't completely abandon the wear based mechanism of nucleation. He stresses that the surface metallurgical changes, what he calls the white etching layer, must also be taken into account. This other mechanism involves cracks forming at the fretted surface, which act as stress concentration notches. A crack eventually penetrates to the substrate [16].

Gordelier and Chiver's approach could be extended to a practical fretting situation. Finite element methods could be used to determine the effect of a given palliative on the stress state. Special elements with coulomb friction capability are available [16]. After the stress state has been determined, other effects such as coating residual stresses, metallurgy, and discontinuities can be taken into account.

3.2 DESIGN.

Many authors suggest that fretting fatigue problems can often be reduced by design of the mating surfaces. As this often involves significantly altering the shape of the contacting parts, its usefulness may be limited to products early in the design stage.

When the slip is of low amplitude, a thin, flexible layer can be put between the two fretting surfaces. Depending upon the modulus and thickness, the shear stress concentration can be significantly reduced. With Hertz contact it is necessary to have a layer on both surfaces. This method has been used successfully in riveted joints [16]. If the flexible layer is thick enough, and the relative movement is displacement controlled, then all fretting wear may be eliminated as all relative movement is taken by elastic deformation of the flexible layer.

Another option involves changing the geometry of the mating surfaces to reduce the shear stress concentration at the surface [16,45,50]. This is often done by removing the material at the edge of contact where the stress concentration would occur [16,8,11]. In

one study, Gordelier and Chivers found geometric stress concentration was more effective than shot peening or graphite-impregnated epoxy resin [49]. Geometric stress concentration is a factor of joint shape, loading method, ratio of clamping to propagating loads, and the coefficient of friction [50].

At times it may be possible to eliminate contact at the worst fretting location without severely compromising other design limitations. An example of this can be seen with a pin joint. Fretting fatigue occurs at the pin locations 90 degrees from the area of the pin with the highest bearing stress. White has shown significant (200 percent) improvements for repeated tension by changing the pin geometry. The pin was shaved at the areas where fretting fatigue occurred so that contact with the plate would be prevented. The effect was much less significant when a large mean stress was included [45].

Smaller geometrical changes such as de-stressing notches also have an effect on fretting [12]. Longitudinal and Lateral notches 0.4mm deep at the contact area prevented fretting fatigue in one study. The unfretted fatigue strength decreased due to the stress concentration of the notches but there was an overall improvement of 100 percent. A unique advantage of this method is that the fatigue reduction due to the notch stress concentration is easily found [16]. One author found a 10 percent increase in life by rounding the edges of contact [38].

The benefit due to de-stressing notches may be influenced by which of the surfaces is notched and the direction of the notches. In one study grooves were placed in the surface of the specimen subjected to fretting and fatigue loads. The specimen was arranged so that only the high points of the grooves were subject to fretting surface stresses. The fretting fatigue strengths were much better than specimens without grooves [51]. Bramhall has shown a similar effect. If the surface not undergoing the fatigue cycling is grooved to reduce the contact area, fretting fatigue strength increases [45]. In another study of Cr-Ni-Mo shaft steel of 480 HV Vickers hardness (polished), fretting fatigue reduction was greater when machining marks were perpendicular to the direction of sliding [52].

A possible explanation for the de-stressing notch effect was given by Waterhouse. He has shown that for one geometry, the fretting fatigue strength decreased as contact area was increased. He suggests this is due to an increased volume influenced by the surface

stress [45]. Another explanation may be that surface grooving or roughening may allow the escape of oxides that are produced [9]. It may be that de-stressing notches are effective simply because they increase the actual contact stress at the interface. This would mean that they are of benefit only in some situations. Perhaps with notches the only cracks that nucleate are located at the tips of notches, away from the bulk alternating stress which could propagate them.

There is disagreement in the literature over whether surface roughening is beneficial to reduce fretting or not [53,54,55]. It is not recommended by one author as even if it is beneficial to fretting, it still reduces the unfretted fatigue strength [11].

The substrate material could be changed at the design stage. One author calculated a 50 percent increase in the fretting fatigue limit by increasing the material fatigue limit by a factor of 2.5 [38]. The hardness of a surface also has an effect on fretting fatigue strength and, like surface roughness, there is disagreement as to the effect of hardness [55]. One source suggests that harder surfaces have greater fretting fatigue resistance [11]. It is further suggested that if two materials are fretted together and only one has an applied cyclic bulk stress, the cycled component should be harder than the other for longer lives. If two materials are fretted against one another and both have applied bulk stresses, the softer material will usually fail first because it is more susceptible to fretting wear damage [11]. Another source states that for smooth surfaces, a hard metal will be more susceptible to fretting corrosion. For a coarse surface, a softer material will be more susceptible to fretting corrosion [55]. Investigators have suggested that two like surfaces will suffer more fretting corrosion damage than two unlike surfaces [55,56].

3.3 MECHANICAL METHODS.

Mechanical methods include processes that cold-work the surface such as shot peening, vapour blasting, bead blasting, surface rolling, dimpling, and ballising [45,12]. They all have the same mechanism of fatigue improvement, viz., residual surface compressive stresses [47,37]. There is much agreement that these methods increase the unfretted fatigue strength and thus increase the fretting fatigue strength [37]. Cracks nucleate much sooner in a peened surface, then propagate a lot slower, if they propagate at all [53]. Many cracks can appear beneath fretting pads that do not propagate due to the

residual compressive stress [51]. One author suggests that the many cracks created by fretting can decrease the stress concentration at all the cracks [57]. Also, shot peening has been used to close porosity in castings [58].

One study suggested that because of its low cost, shot peening was the preferred method of inducing residual compressive stresses. Work hardening was found to extend deepest in cold rolled items [47].

It is possible for the beneficial residual compressive stress to be lost during manufacture or use of a cold-worked surface. The microstructural effect of peening is to make dislocations. These dislocations may nucleate precipitates which can impede further dislocations. If 7075 is aged after it is peened, then some residual compressive stress is lost and both fatigue and fretting fatigue strengths decrease. Some characteristics of 2014 are similar but it is better than 7075 in one way, 2014 can be aged after being peened and not lose much fatigue strength. The precipitates of 2014 will pin dislocations more effectively than those in 7075. The compressive stress induced by peening also can be eventually lost by fading, a result of the alternating stress [53].

Other possible beneficial aspects of shot peening to fretting fatigue include the increase in hardness and the rough surface. As previously mentioned hardness can be beneficial to fretting fatigue. It may limit cold welding at contact points [57,16]. The rough surface may act as de-stressing notches. Another report suggests a rough surface decreases fretting fatigue life [57]. The rough surface may be of benefit when lubrication is used as it creates small pockets of oil [16].

Shot peening produces both surface hardening and residual compressive stresses. Since both are beneficial to fretting fatigue one investigation attempted to determine which was the dominant factor. It was found that the residual compressive stress was the dominant mechanism of fretting fatigue reduction and that work hardening plays only a very minor role [20].

Shot and roll peening stand out because they are the only reliable methods of fretting fatigue improvement [37]. Although there are reports of unfretted fatigue strength decreasing at times due to peening the surface too much [51], reports of fretting fatigue

reductions due to cold working are rare [59]. Some investigators have tested cold working on aluminum, magnesium, and titanium parts and report improvement in fretting fatigue [47,51]. Other reports have shown successful use of peening on carbon steel, stainless steel, and 3.5Ni-Cr-Mo-V [49,45,57].

Alumina blasting also improved fretting fatigue somewhat [51]. Glass bead peening also has proved to be beneficial. One report showed an increase of a factor of three for the fretting fatigue life of 2014A and was the most effective treatment they could find [60].

Work-hardening capacity may play a large role in the effectiveness of shot peening. Waterhouse has reported that with stainless steel peening has little effect on plain fatigue but can create fretting fatigue strengths as high as plain fatigue [45]. They found that steel did not have as much fretting fatigue improvement due to shot peening as the stainless steel. The fretting fatigue strength of the steel approached 60 to 80 percent of the unfretted strength. They attributed this to the lower work hardening capacity [45,57].

At times the fretting fatigue strength of peened stainless steel can even be higher than the plain fatigue of the peened material. The authors suggest this may be due to many cracks forming and decreasing the stress concentration at all of them [57].

For inside holes, stress coining may be more appropriate than peening. There are several methods of coining used depending upon the geometry and size of the surface to be coined. Generally a lubricated expansion pin is forced through an undersized hole [61].

One other possible fretting fatigue palliative is fretting wear itself. It is possible for fretting wear to occur rapidly enough to remove any nucleated cracks before they can propagate [47]. Although this method could be used to prevent fretting fatigue, due to the loss of material, component lives would usually be less than the fretting fatigue life.

3.4 CATHODIC PROTECTION.

In some applications it may be reasonable to consider cathodic protection as a palliative. Nakazawa et. al. found that cathodic protection greatly increased the fretting fatigue life of high strength steels in seawater. They attribute this to a decrease in crack

propagation not associated with fretting. They suggest calcerous deposits had a crack closure effect [62]. Another study of fretting of high tensile steel wires showed dramatic reductions in wear rates when cathodic polarization was used in seawater [63].

3.5 COATINGS, LUBRICANTS, AND SURFACE TREATMENTS.

As previously stated, there is a lot of disagreement in the literature over the performance of different coatings [16,64]. These disagreements may simply be due to different testing methods.

The effectiveness of coatings often is thought to be due to increased hardness or to create residual compressive stresses [9]. Other theories are that coatings reduce frictional stress or absorb some movement [47]. One author suggests that the role of surface coatings may be to alter the surface roughness and stress state. He suggests this may have an influence on whether the surface behaves elastically or plastically [46]. Some authors doubt that the effective mechanism of using coatings to prevent fretting fatigue is to prevent wear damage since little wear damage is necessary to nucleate cracks [47]. The purpose of coatings is not always to prevent metal to metal contact. Fretting occurs even if only one of the materials is metal [65].

A common explanation for the choice of palliative is how it changes the coefficient of friction. The determination of whether increasing or decreasing the coefficient of friction is beneficial is dependent on geometry, slip regime, and the controlling factor of the relative movement [37]. There is also disagreement over the best coefficient of friction for mechanically fastened joints. Some investigators have found that decreasing the coefficient of friction in a joint decreases the fatigue life. They suggest this is due to the fastener holes taking an increased percentage of the total load because the load cannot be taken by friction [47,45]. Another study has shown greatly increased fatigue lives of joints when PTFE (polytetrafluoroethylene) was used [61]. It may be that the increase in life due to introduction of PTFE would have only occurred at low stress levels and that if stress levels were increased they too would see a reduction in fatigue strength.

3.5.1 Solid Coatings.

Solid coatings are commonly used palliatives not so much for their strengths but due to the limitations of other choices. Low adhesion is

a common problem with solid coatings. Sikorsky suggests the factors that contribute to low adhesion of metals on a substrate are low hardening coefficient, high hardness, high elastic modulus, high melting point, high recrystallization temperature, small atomic radius, and high surface energy [66]. Coatings are often limited by fretting wear rates [60,64]. It is often necessary to consider whether a coating can be repaired if damaged [44].

3.5.1.1 Hard Metal Coatings.

Some sources suggest that hard metal coatings should not be used to reduce fretting fatigue effects as there is often a significant reduction in the unfretted fatigue strength associated with applying a hard metal coating [67,16,68]. This is often the result of voids in the coatings and residual tensile stresses. Some authors have successfully used hard metal coatings by eliminating the unfretted fatigue strength reduction problem. Some suggest using thermal diffusion to allow residual stresses to decrease [45,69], others suggest shot peening before plating [70,45].

Often, the theory behind using hard coatings is to reduce the area of real contact [45]. Although this theory works well for fretting wear it has not been shown to be true for fretting fatigue.

When a metallic coating with a lower yield point than the substrate is loaded, cracks can form in the coating before the substrate is loaded near its yield point. These cracks in the coating will then act as stress raisers to nucleate cracks in the substrate. When metallic coatings are harder than the substrate (chromium or anodize), they often contain microcracks and will act as notches [71].

Since chromium coatings are commonly used to decrease wear, it appears as though they have been tested in fretting situations more than other hard coatings. The literature generally seems to agree that chromium coatings reduce fretting wear, but have been reported to be abrasive to the material they rub on [54,72,73,74]. There is a lot of disagreement in the literature over the effectiveness of chromium coatings to reduce fretting fatigue. Everything from seeing a considerable benefit, to slightly beneficial, to decreasing the fretting fatigue strength [37,47,44,72,66,16,70]. Low performance was often blamed on discontinuities or residual stresses [66,16,47]. In one study by Alyab'ev et. al. they reported that residual compressive stress was the reason why one of the high alloy

chromium steel coatings had the best fretting fatigue characteristics [70].

There was a similar confusion in the literature over nickel coatings. At times nickel appeared to help fretting fatigue, at other times it didn't [47,69]. One study on using an interdiffusion heat treatment does make the use of a Ni-Co coating look promising, but expensive [69]. Another report showed nickel plating of gears on shafts eliminated fretting fatigue [12]. Reports once again agreed on the beneficial effect of nickel coatings on fretting wear, at times reducing wear by an order of magnitude [44,69].

One author suggests that for metal coatings, hard ones such as cobalt bonded tungsten carbides had the best fretting fatigue performance [45,44]. It should be taken into account that the specimens had been vapour blasted or shot peened. It was suggested that the effectiveness of this type of coating is dependent on hardness and properties of the dispersed phase. Oxides, the dispersed phase, can reduce the coefficient of friction [44]. Another report agrees, fretting fatigue of titanium has been successfully aided by plasma-sprayed and detonation-gun-deposited tungsten carbide in a cobalt matrix [47]. One should be wary of this as another author reported that for fretting wear cermet coatings were no better than steel substrate alone [75]. One report stated that tungsten carbide was not effective. Chromium carbide and titanium carbide were found to wear very little when fretted [74]. It is unknown whether fretting wear is any indication of fretting fatigue, but given the history of hard metal coatings, it is better to be cautious.

3.5.1.2 Soft Metal Coatings.

The literature ordinarily agrees that soft metal coatings have no effect or some improvement [37,64,49]. Even if a soft metal coating has been shown to be effective, they usually have an unacceptably short lifetime (Au, Ag, Cu, Cd, Pb, In, also Ni and Cr) [49,47,64]. A study suggests that wear occurs rapidly until the metal coating reaches about 0.1 micrometer. Wear may slow due to the inability of dislocations to build up [47].

One theory behind using soft metal coatings suggests low friction can be obtained due to their low shear strength [45,16]. Another theory suggests the success of the soft metals may be due to the lubricating properties of thin soft metal coatings on a hard substrate. The

coefficient of friction can decrease with increasing load [47]. Some suggest soft metals reduce fretting as their high coefficients of friction may result in seizure. Soft metals with high coefficients of friction which may be susceptible to seizure include silver, indium, and lead [16].

The most common aluminum coating is cladding. When fretted against steel, it took a clad aluminum alloy surface 23 times the fretting cycles to nucleate a crack as it took an Al-Zn-Mg alloy [45]. Another study found that aluminum with 1 percent zinc sprayed onto an aluminum surface increased the fretting fatigue resistance. Cracks did form in the coating but spread laterally in the coating or along the coating-substrate boundary. There were no observations of cracks making it into the substrate [51]. Aluminum coatings also have good resistance to atmospheric corrosion and immersion in seawater. However, they are susceptible to pitting. When aluminum is used on steel, however, the pits are lagged by iron oxide corrosion product and are not much of a problem [65]. An ion-vapor-deposited aluminum has been developed by McDonnell-Douglas. However, it was developed for reasons other than fretting and it is unknown whether any fretting data exists [76].

Since steel aerospace fasteners are usually cadmium plated it's surprising there isn't more information about fretting of cadmium [76]. It is likely used instead of zinc as it is more resistant to a marine environment [65]. One study on fretting corrosion showed that cadmium outperformed indium, copper, hard nickel and chromium over a short time period, but did not outperform silver [64].

Sprayed molybdenum on steel rod was found by Waterhouse to decrease the unfretted fatigue strength but increase the fretting fatigue strength [66,45,47]. The coating had voids and appeared as if it was applied in layers [66]. Another study showed that flame-sprayed molybdenum on bare steel resulted in fretting wear rates at least 2 orders of magnitude less than samples of bare steel. However, increasing the temperature decreased wear rates of steel but increased the wear rate of the coated surfaces by an order of magnitude [44].

In one study, copper coatings on Ti-6Al-4V showed no fretting fatigue improvement at thicknesses less than 5 micrometers. Significant improvements were found for thicknesses from 15-20

micrometers. Thick aluminum coatings, 35 micrometers, also helped fretting fatigue strength but not as much as the copper [59]. Waterhouse also found that copper coating effectiveness increased with thickness of coating [47]. This would suggest that the copper may be acting by re-distributing stresses. Gordelier and Chivers used metallic shims 0.8mm thick to redistribute stress concentrations and aid fretting fatigue life. They found it was effective at reducing fretting fatigue in 3.5Ni-Cr-Mo-V [49]. Copper-Nickel-Indium coatings increased the fretting fatigue strength of titanium about 10 percent [45]. One study suggests that the wear lifetime of copper is low [49].

One study suggests that silver has better wear properties than cadmium, indium, copper, hard nickel and chromium [64]. Another study states that silver has been used successfully on a titanium/steel bushing, but the plating technique must be carefully chosen as a large unfretted fatigue strength reduction can occur [47]. Another study suggests that silver was not effective due to oxidation [77].

When gold was used as a palliative it failed by low adherence when ion plated or electrolytically deposited on 3.5Ni-Cr-Mo-V. There was no difference in performance between the two methods [49]. However, another study states that gold ion plated films had better wear characteristics than silver [77].

3.5.1.3 Polymers.

Polymer coatings are usually used as a wear buffer or as a self-lubricated coating [67]. Thick sections of polymer also can be used to redistribute stresses. Another theory of using non-metallic coatings is to prevent local welding [45].

Polymer coatings can fail by debonding from the substrate, general plastic wear, chemical degradation, or by the formation of cracks in the film allowing access to the substrate [78,79].

Fretting wear rates of many polymers increase with increasing humidity. One study of polyvinyl chloride showed that film life was 15 times longer at 17 percent relative humidity than at 58 percent. A study on the effect of surface finish showed the shortest film lives were obtained when sliding was perpendicular to the lay of ground surfaces [78].

Fretting can still occur between a polymer and a metal if oxide particles are embedded in the polymer [45,16,80]. The oxides then wear the fretting metal [16]. This is in spite of the fact that some evidence shows abrasion has only a minor contribution to surface damage [64].

A study of many thin polymer coatings on steel consistently showed that polyvinyl chloride had the longest wear life. There was evidence that hydrogen and chloride from the PVC combined to make hydrochloric acid, thus discoloring the coating. The authors suspected the long wear lives may have been due to electrochemical or chemical effects of the chloride [78]. Caution may be necessary when using PVC on aluminum or stainless steel as the chloride may induce pitting or stress corrosion cracking.

Epoxy resin has been used by Nishioka and Komatsu to increase the fretting fatigue of press-fit steel by 30 percent. Epoxy resins used to secure threaded fasteners have also been used successfully to reduce fretting [45]. Another study showed that epoxy with dispersed oil had much better performance than TiC or Tiolube coatings [81].

A laminate of phenolic resin and cotton was effective between steel and aluminum [47]. Plastic shims 0.003 inches thick were made of terylene "melinex". All fretting effects on fatigue were reported as being eliminated. The thickness required was dependent on surface roughness and pressure applied [51]. In another investigation of a thin terylene sheet between two aluminum alloys fretting was prevented [11].

In one investigation of titanium coated with polyimide fretted against bare titanium, the wear rate of the uncoated titanium surface decreased at least a couple of orders of magnitude [67]. In another study on polyimide on steel, the polyimide did not damage the steel and had relatively good performance. Evidence was found of the polyimide transferring to the opposite surface [78].

Ivanova and Veitsman have used a synthetic rubber coating on stainless steel to get a 60 percent increase in fretting fatigue strength [45]. Johnson and O'Connor placed rubber at a fretting interface and completely eliminated fretting fatigue. The experimenters explained their results with a stress analysis [47].

When polymers are tested for fretting resistance they are often combined with a solid lubricant. Several cases are discussed in the solid lubricants section. Most investigators report improvements by adding solid lubricants but this is not always true [67].

3.5.2 Lubricants.

Lubricants are helpful when the fretting motion is displacement controlled. For liquid lubricants to be successful over a sustained period they must be continually replenished [16]. Liquid lubricants that are not replenished can significantly alter fretting behavior over a short period [10]. A thin penetrating oil may be the only choice when the contacting surfaces cannot be separated. Solid lubricants (molybdenum disulphide, zinc oxide, graphite, PTFE) can be very effective but have a limited lifetime [16]. Some theories behind the mechanisms of lubricants are the reduction of friction and environmental exposure [9]. These traits are not always beneficial. Reducing friction can allow greater slip amplitude and lead to an increased wear problem overall [16]. Reducing environmental exposure may limit the production of protective oxides.

Dry, low shear strength coatings with solid lubricants appear to be much more successful than oils or greases [9]. However, even solid lubricants in resins are limited. Molybdenum disulphide, EP grease, and bonded graphite were all shown to be ineffective in fretting [64]. Molybdenum disulphide, graphite and PTFE were placed in greases and resins but were protective for only a short time as the material would squeeze out from the surfaces [51].

3.5.2.1 Solid Lubricants.

Solid lubricants often are used due to the limitations of less viscous lubricants, and because they are the only choice of lubricant when access to the fretting surfaces is impossible [9]. Solid lubricants can be very effective with fretting but have a limited lifetime. Solid lubricant coating effectiveness is totally dependant upon the specific application [16]. The stress-based theory for the mechanism of fretting may explain this. Variables affecting the effectiveness of solid lubricants include substrate metallurgy, stress levels, and the environment [9].

Because molybdenum disulphide is a common solid lubricant it has been tried in many fretting applications. It can be used in a vacuum but becomes abrasive above 750 F [76]. Sputtered molybdenum disulphide in one study was very sensitive to moisture content. High moisture nearly eliminated the benefits of molybdenum disulphide [67]. Other investigators found that if molybdenum disulphide is used on steel against steel, the lifetime is not dependant on load [81].

Molybdenum disulphide has been shown to decrease wear rate for a finite time [45,54]. However, when it is used to prevent fretting fatigue it is usually combined with some type of binder and bonded to a surface [9]. Although the lifetime of molybdenum disulphide is greatly extended by placing it in a binder it is usually the wear rate of the coatings which limits their fretting fatigue usefulness [47,59]. The wear rate of the binder-molybdenum disulphide mix can even be greater than the binder by itself. In one study the wear rate for polyimide increased as solid lubricants were added [67]. A favorable report stated that some resin bonded coatings containing zinc chromate, molybdenum disulphide, graphite, or PTFE were found to be completely effective against fretting [51]. Some investigators tested the fretting wear rates of molybdenum disulphide in a variety of resins and did not obtain the wear endurance of 100,000 cycles they wanted [47]. There was another confusing report of a phenolic resin with molybdenum disulphide and zinc chromate being "completely protective" and yet fractures still occurred at the contact area [51]. Perhaps it is suggesting no fretting wear occurred but that the coating did not prevent the effect of the contact stress state. Another report found that adding molybdenum disulphide to a polyimide both decreases the coefficient of friction and increases the strength of thin films [80].

Harris has found molybdenum disulphide in an epoxy resin used on aluminum to increase the fretting fatigue strength up to the level of the unfretted fatigue strength [45,47]. Bowers had success with fretting fatigue of a Al-Zn-Mg alloy by using resin with ZnCrO₄ and molybdenum disulphide [47]. A phosphate etch primer containing MoS₂ has been beneficial on aluminum [12]. Bowers did suggest, however, that he had better success with PTFE [47]. Alyab`ev et. al. have found PTFE with molybdenum disulphide or graphite to be effective in fretting fatigue if put on only one of the fretting surfaces. They had much more success with steel than with aluminum [45]. Nix and Lindley used 'molycote 106' solid lubricant with molybdenum disulphide on 2014A and saw a limited fretting fatigue

effect due to wear [60]. One report found that of the coatings tested for fretting wear, Rh + MoS₂ coatings with low pressure against Be were most effective [81].

A report on anti-fretting compounds for aluminum found two combinations of coatings which provided full protection. The first was a chromate filming treatment (Alocrom 1200), followed by isocyanate-epoxy resin loaded with molybdenum disulphide (air cured). Adding chromates (leachable chromate) reduced the anti-fretting properties. The second is an epoxy resin loaded with molybdenum disulphide which is cured at 150°C with carbon fibre resin mats [82].

PTFE is a soft material, as such it deforms easily and is not suited to high load structures [16,54]. Even in cases where PTFE does not immediately squeeze out of the joint, materials with PTFE are often reported as being limited by wear rate [47,60]. Although there are cases where PTFE has been used successfully alone [47,80], it is usually mixed with something much harder. In one report Teflon fabric, Teflon fiberglass fabric, and Teflon in an inorganic resin were all found to have inadequate wear rates [47]. Acheson 'Emralon 810' with PTFE was also limited by fretting wear [60]. Fretting corrosion of PTFE in epoxy, enamel, and polyimide was studied. The best results were obtained with PTFE-epoxy [64]. PTFE with glass powder added for mechanical strength was used and reported to show no fretting wear [54]. One theory suggests the reason why PTFE can be effective is that it can form a film completely around debris particles. It is also possible to put PTFE in sintered phosphor bronze matrix and electroless nickel [16].

Sandifer tried Teflon, molybdenum disulphide filled nylon, and ceramic filled Teflon in aluminum lap joints. They were effective at reducing fretting but whatever gains were made by having no fretting were lost due to the increased load taken by the pins. The fatigue strengths remained unchanged [45,47].

Graphite is also a common lubricant but it has some limitations. Coatings with graphite in them were found to corrode aluminum [51]. Also, graphite acts as an abrasive unless oil or water are present. Therefore, graphite should not be used in a vacuum or at high temperatures where the liquid could boil off [76]. To increase wear life graphite is also often bound in a resin [54]. However, one report suggests that adding graphite to a binder (polyimide) can increase

the wear rate of the binder [67]. Gordon and Chivers found that polyimide resin with graphite improved fretting fatigue of 3.5Ni-Cr-Mo-V but not as much as epoxy resin with graphite [49].

3.5.2.2 Greases.

One theory behind the use of greases is that they act as a reservoir of oil. This oil then can move to the area of asperity contact. The life of grease is not only determined by loss of volume between the contacting surfaces, but by the increasing concentration of wear debris in the grease [9].

Shear resistant greases were found to be much less effective than softer greases in reducing fretting wear. Fretting corrosion of bearing races was found to decrease as viscosity of the grease decreased [83].

Common additives to grease were not always found to be of benefit. Metal soap bases (ZnO, MoS₂, tricresyl phosphate) were not found to reduce the wear rate [83,54]. Roechner and Armstrong found that adding graphite or MoS₂ to grease increased wear [83]. Extreme-pressure additives decreased wear rate in one study. But, phosphoric acid etch had the same effect [54].

Overd found that MoS₂ in a lithium stearate grease did reduce fretting fatigue of aluminum [9]. A bearing company had good success with a lithium soap grease on races. Lithium grease also helped with aircraft control bearings. However, a test of helicopter components showed that a sodium-calcium mixed base grease was much better than some lithium soap greases [83]. On aluminum, resin bonded coatings were found to be more effective than greases [51].

3.5.2.3 Oils.

Success with liquid lubricants is dependant on the ability to continuously re-supply the lubricant to the interface [9,73]. One study showed that oil was completely successful at eliminating fretting corrosion when it was continually applied at the surfaces [64].

Increased viscosity of pure mineral oils decreased wear rate. However, artificially increasing viscosity with VI-improvers

increased the wear rate [54]. A study by Rubin showed that film thickness and film strength affected the amount of oxide formed. Film strength can be increased with additives like tricresyl phosphate [83].

Some investigators have found that mineral oil can be effective [9]. Experiments demonstrated that fretting corrosion was reduced from 20 to 50 percent by a simple wipe of mineral oil [64]. Almen stated that fluid lubricants greatly reduce fretting corrosion. He also found that submerging the specimens reduced wear. Dies used paraffin oil and found no significant wear [83].

In one study of mineral oils on steel, friction and fretting wear were greatly reduced when 2 percent zinc dialkyldithiophosphate (ZDDP) was added to the lubricant. Zinc di-n-octyldithiophosphate was the most effective ZDDP for reducing fretting wear [84].

A study of ester lubricants showed that the wear rate is not directly related to the amount of acid or peroxide in the lubricant. The authors suggest wear is related to an intermediate peroxy radical. Antioxidants in lubricants may function by eliminating these peroxy radicals. Fretting tests on steel with an ester lubricant containing an antioxidant additive (zinc diethyl dithiocarbamate) showed that increasing antioxidant significantly decreased wear rate [85].

3.5.3 Surface Treatments.

Surface treatments include carburizing, nitriding, phosphatizing, sulphidizing, ion implanting, and anodizing [9,45]. They have been tried alone but often with other palliatives. Waterhouse has obtained five times the life to propagate a crack if an oil-in-water emulsion is used on phosphate or anodized surfaces [45].

3.5.3.1 Anodize.

Anodizing has been shown by investigators to improve wear performance [47]. However, one author suggests all anodizing operations decrease fatigue life, perhaps due to microcracks in the coating [58]. Shot peening has been used successfully prior to anodizing. The shot peening provides fatigue resistance, the anodizing provides wear and corrosion resistance. In some cases the combination of shot peening and anodizing can have improved fatigue performance over the untreated metal [58].

In fretting fatigue conditions performance is either unaffected or reduced by anodizing. There may actually be some improvement but it is counter-acted by the unfretted fatigue reduction associated with the anodizing [47]. Syers also found that both anodizing and anodizing with epoxy resin and MoS₂ did not help the fretting fatigue strength of titanium [45].

3.5.3.2 Ion Implantation.

Besides introducing a particular ion into a substrate, ion implantation has several side-effects that must be considered. Among them are ejection of high energy atoms (sputtering), increased surface temperature, and generated discontinuities in the lattice [86].

Ion implantation has been shown to reduce the wear of metals and lower the coefficient of friction. This may be due to the ions affecting the adhesion characteristics [9,45]. Ohmae et. al. plated gold, silver, and boron carbide to determine their fretting resistance. Ion plated films had better fretting properties than both sputtered and vacuum evaporated films [77,45].

One study investigated the fretting wear of Al-Bronze aromatic polyester, WC-Co, Al₂O₃-TiO₂, and Cr₂O₃. The Al-Bronze aromatic polyester was the most effective wet or dry but it was the only sacrificial coating. Al₂O₃-TiO₂ was the only hard plasma sprayed coating to have a decrease in fretting wear on the uncoated surface [67].

In one study, when ion implantation was used with carbon ions in titanium, the resulting TiC particles averaged 100A in size. Significant fretting improvements were made. The mode of failure did not change [87]. Another investigator found that the maximum fretting benefit from ion implanting titanium occurred when second phase precipitation occurs. It was suggested that the effect of ion implantation on fretting fatigue is more likely due to changes in wear properties than changes in fatigue properties [86].

Gordon and Chivers found that ion plating on 3.5Ni-Cr-Mo-V was no better than conventional electroplating for fretting fatigue [49]. When barium, caesium, strontium, and ytterbium were ion implanted, small increases in fretting fatigue strength have been

observed [45]. Ti-6Al-4V was ion implanted with N⁺, and N⁺ and Ag⁺ ions, there was no change in fretting fatigue behavior [59].

3.5.3.3 Sulphidize, Phosphatize, etc.

This category includes sulphidizing, phosphatizing, carburizing, carbonitriding, nitrocarburising, and gas nitriding. Carburizing, carbonitriding, nitrocarburising, and gas nitriding increase the surface hardness and increases both adhesive and abrasive wear resistance. They can also affect the friction coefficient and can induce a compressive residual stress and thus increase fatigue life [16,45]. Carburizing and nitriding create intermetallic compounds [45]. Although they are capable of creating residual compressive stresses, diffusion treatments can also lower the unfretted fatigue strength by a factor of 2 or 3 [45,12]. A nitrogen diffusion treatment containing sulfides was shown to be ineffective in decreasing fretting corrosion [64].

Sulphidizing is said to produce residual compressive stresses [37]. There is much agreement that sulphidizing improves fretting fatigue performance. This may be due to increased unfretted fatigue resistance resulting from the compressive stresses. Improvements from 135 percent to 500 percent have been observed by investigators [47,45].

Phosphate coatings have been examined for fretting conditions as they show good wear resistance in continuous sliding and fretting wear. Some investigators found markedly reduced fretting performance while others found it to be of considerable benefit [37,47,12]. Phosphate coatings are applied with a dilute solution of phosphoric acid. Crystalline phosphate forms on the surface from the phosphoric acid [76].

4. APPLICATIONS TO JOINTS.

This section covers investigations into the role of fretting which are specific to joints commonly used in aircraft.

4.1 OBSERVATIONS OF FAILURES AT FASTENERS.

The following failures occurred due to a crack from a fastener hole [27, 97]:

The two Comet crashes in 1954
The milk bottle problem on the B-47
B-52 wing and fuselage problems
F-111 wing problems
C-5 wing problems
737-200 cold bonded joints

It is unknown whether fretting was involved with these incidents as investigators often do not look for fretting.

One author suggests fretting occurs in different stages at all joints [98]. Although the damage is not always large enough to be the cause of failure, another author found that 90 percent of failures originated where fretting was possible. Other authors have positively identified cracks that are the result of fretting [12,41,56]. The increased frequency of fretting failures has been attributed to the higher strength, performance, and durability required and increased attention to failure examination and failure modes [99].

4.2 ARGUMENTS FOR FRETTING BEING THE WEAK LINK IN A COMPLEX FATIGUE SITUATION.

With simple fretting tests the affect of fretting is readily apparent as the coupons are designed so that fretting is easily the worst fatigue critical detail. With joints the failure analysis is much more complex as many different mechanisms are present to nucleate a crack. Fretting at one location may not nucleate and propagate a crack before another crack nucleates by a mechanism other than fretting. Other details include decreased net sections, stress concentrations, corrosion fatigue, etc. The effect of fretting on fatigue is often larger than both the effects of a reduction in area due to a fastener hole, and the stress concentration at a hole [100]. Some tests show that by eliminating fretting, joint fatigue strengths can increase up to 90

percent [56]. Another investigator suggests that the full benefits of new fastener systems and hole preparation techniques can only be apparent if fretting fatigue failures are eliminated first [27]. A study of lugs, which are similar to mechanically fastened joints, showed that when fretting occurred, cracks 1 mm long were present after only 20 to 60 percent of the life of the component. Compare this with the findings of other authors that when fretting was not possible, cracks only 1 micrometer in length were present after 80 to 95 percent of life [41].

Additional problems with predicting fatigue life of joints include calculating residual stress from cold worked holes, and calculating frictional forces [101].

Predicting the effect of fretting on a particular joint during service is also difficult as the testing conditions can alter the mode of failure. Single rivet specimens do not give accurate results for fatigue [12]. Bending stresses tend to mask fretting fatigue damage [56]. Also, constant amplitude loading is not adequate for large scale components. Although spectrum loading is more accurate, it takes up to 10 times longer to complete a given test and is more expensive for a given hour of testing [27].

There are many commonly observed indicators which can suggest if fretting has occurred in a joint. The location of crack nucleation can help discriminate between fretting failures and other causes of failure. Failures in joints often occur at fastener holes or at sites of fretting damage [68]. Fretting can occur inside a fastener hole. However, if a crack nucleates in a hole it is not substantial evidence that fretting was the cause. The stress concentration from the hole and/or the increase in stress due to the decreased net area could have been the cause of crack nucleation. Cracks often nucleate away from fastener holes in aircraft joints [100,56,27,102]. It is a good indication that fretting may have been the cause of failure when cracks nucleate away from the fastener hole. If they do, this means the fatigue reduction where the crack nucleated must have been greater than the combined fatigue reduction at the fastener hole. When cracks nucleate away from the fastener, they are often found in the zone most heavily damaged by fretting. Slip around a fastener varies with the radial distance due to fastener pre-load and normal pressure. Fretting fatigue will often nucleate at the radial location of worst combination of pressure and slip [56].

Debris characteristic of fretting is not conclusive evidence that fretting was the cause of crack nucleation, but it does prove fretting was present and could have been at least partly responsible. Fretting debris has been found in many test specimens characteristic of aircraft joints, and in full-scale aircraft fatigue tests [100,103]. Aluminum will form either extremely fine black powder or could form coarse chips. Fretting of titanium will often result in a very fine brown powder. Titanium third bodies are cohesive and compact [10]. Fretting debris for non-oxidizing steel is a rust colored powder [74]. Steel third bodies are loose and non-cohesive [10].

One study has found that fastener hole roughness and burrs do not affect the fatigue life of a fastener significantly [27,102]. This is a surprising result as roughness at locations other than fastener holes has been found to decrease the fatigue life. Perhaps what is occurring is that both roughness and fretting act mainly during the nucleation of a crack. Hole roughness may not decrease fatigue life because fretting is already present and will nucleate a crack before the mechanisms associated with the roughness or burrs could. Some authors suggest drilling a hole strain hardens a small layer and thus increases fatigue life. The same authors suggest that if heating is too great or there are score marks, fatigue strength may decrease [71].

4.3 INFLUENCE OF TREATMENTS COMMON IN AIRCRAFT JOINTS.

The fatigue effects of many common substances found in aircraft joints have been tested. Besides affecting the unfretted fatigue strength, they can greatly influence fatigue life by altering the coefficient of friction between joint surfaces. Even with fasteners such as rivets there is some clamping of the adherends by the pre-stress of the fastener [12]. This clamping results in a significant portion of the load transfer by friction and not through the fastener shank. Many substances used with a joint affect the fatigue strength by modifying the coefficient of friction and thus the ratio of load transfer taken by the fastener and friction. Lubricants used to reduce friction and thus fretting fatigue, often decrease fatigue life by significantly increasing the stress at fastener shanks [56,71].

To reduce fretting, some investigators have attempted the opposite approach, to increase the coefficient of friction so that all non-elastic relative movement is eliminated, thus eliminating fretting without placing more stress on fasteners. However, it must be remembered that all relative movement must be stopped. Failure may still occur

even if 99 percent of movement has been stopped [12]. One investigator determined that a fastener designed to take all the load in friction by pre-stressing the fastener would weigh 7 times what a fastener which transfers the load by shear through the shank weighs [104].

A loss of load transfer by friction also can occur from plate warpage, burrs, not enough clamp up during drilling, or debris that result in a gap between sheets in a joint. Gaps have been shown to affect the fatigue life [27].

Faying surface sealants are commonly found in many parts of an aircraft. They often are used for their sealing properties in fuel tanks and in exterior surface joints. They also have been observed to significantly affect fatigue lives. There are different faying surface sealants used in different applications. Many are made with polysulfide to inhibit corrosion [27]. Some sealants may act as adhesives, which have been found to significantly increase fatigue life. Some are so flexible they reduce the load transfer taken by friction and decrease fatigue life at the fastener [103]. Flexible sealants have been found to behave much like lubricants. Flexible sealants will decrease life when load levels are high, and increase life when load levels are low [105]. One study found that as faying surface coating thickness was increased, the fatigue life decreased [27]. Given the evidence of the large effect sealants have on fatigue life, it is surprising that very little information is available on the fatigue effects of different faying surface sealants.

Adhesives used in joints have been found to significantly increase the fatigue lives of joints. One study found a 65 percent increase in life at 10 million cycles [12,56]. One author suggests that a reduction in fretting is highly suspect for the increase in life as adhesives are particularly favorable at very high cycles [12]. Only adhesives can reduce the load transfer to the fastener and reduce fretting corrosion [71].

Even when fretting does not occur, there is evidence to suggest adhesives would be beneficial. One study found that the use of adhesives in joints improved the fatigue life by mechanisms other than fretting. Adhesive bonding was found to have more effect on fatigue than either cold expansion, coating the surface of the hole with adhesive, or the use of close fit rivets [106,107]. The authors suggested that fretting was not the cause of failure as un-bonded

specimens had fretting debris at or near the countersink end of the fastener and cracks usually nucleated at other parts of the fastener. They suggest the favorable fatigue characteristics were likely due to reduced hole stress concentration and reduced stress intensity at the crack tips [106].

Another study was conducted in which an adhesive was placed on joint parts and allowed to cure before the joint was assembled. It did prevent fretting but the fatigue strength remained nearly the same due to load transfer to the bolts [56].

The use of adhesives in practical joints is limited by the necessity to remove fasteners for inspections, modifications, or repairs [15].

Other common compounds found in aircraft joints are penetrants used for corrosion protection [103]. All common penetrants used (e.g. Ardrox-3961, LPS-3) contain high molecular weight hydrocarbons, a solvent with low surface tension, and a corrosion inhibitor [103]. Penetrants often are applied by aerosol. These products are applied both at the factory and during service. They penetrate cracks, displace water, and leave behind a soft waxy residue [103].

There have been many investigations on the effect penetrants have on the fatigue life of aircraft joints. Penetrants have been found usually to reduce the fatigue life, presumably by reducing friction and thus increasing the load transfer at the fastener. They also have been found either not to affect fatigue life or to improve it [41,103,108,109,110]. One study suggests there is no significant difference in detrimental fatigue characteristics between the two types of penetrant [103].

A test was conducted to determine how effective penetrants are at entering a common commercial aircraft joint. Riveted joints from Lightning aircraft which had been used in service were obtained (Celloseal QH in the interfay). Dyed or fluorescent penetrant was sprayed on while the joints were unloaded. The joint was then disassembled. Significant penetration into the joint was found. The majority of penetrant entered at the edge of fastened sheets but some entered between the fastener and fastener hole. At times penetrant found its way all the way across the joint [103]. A similar study also found penetrant over a large area of the joint [110]. In another study penetrant was applied to joint parts, the joints were

assembled, then fatigue tested. After disassembly it was found that specimens with penetrant had a circular pool of black liquid surrounding each rivet hole. The authors hypothesized it consisted of penetrant and fretting debris. The specimens with no lubricant had a smaller ring of black discoloration [108].

Several mechanisms have been proposed on how penetrants affect fatigue life [108, 103,109]:

1. Loss of friction results in more load being transferred to the fasteners.
2. The penetrant lubricates the surfaces, transports debris, and thus changes the fretting action.
3. Penetrant may allow debris to enter a propagating crack and act as a leverage support in the crack.
4. Chemical reaction occurs at the crack tip.
5. The penetrant isolates the crack from the environment.

One author suggests that the first explanation is the most likely because failure often occurs at fastener holes after application of penetrant [108]. Other authors suggest that although penetrant was at the locations of fretting, the penetrant did not alter the fretting patterns and thus some of the above mechanisms would not be dominant [110].

Since clamping in rivets is concentrated near the head and decreases rapidly as distance from the fastener is increased, the author suggests the reduction in friction due to penetrant is only important near the fastener head. Penetrant can reach this area from the countersink or head of the fastener. Fatigue failures have been observed in which there was fretting debris at the head of the rivet [103].

In one study a penetrant's effect on the fatigue of various joint geometries and fastener types was tested. Failure occurred at clamping areas, fastener holes, and rivets. It was found that the penetrant's affect on fatigue was dependant upon the design of the joint, the maximum load, and the slip. At times penetrant increased life, sometimes it had no effect and at other times it decreased life

[110,109]. At times penetrant was also found to change the location of failure. For instance, lap joints without penetrant failed in the sheet. When penetrant was applied, failure occurred in the rivets [110].

Another study investigated the effect penetrants had on different types of sealants. Unbonded joints (metal to paint) had an average reduction in life due to penetrant of 50 percent [103]. For sealed joints (a cold bonding compound) there was deep penetration in the joint. The interfay sealant appeared to be porous. There was a small fatigue reduction. Hot bonded joints (hot cured interfay) had no cracking at rivet holes. A significant portion of the load path was not through shear in the rivets. Cracks originated at the edge of the bond line where there was 'severe' scratching normal to the loading caused by the surface preparation. There was no penetration of the penetrant into the joint. No change in fatigue performance due to penetrant was found. The author suggests that it is unknown whether the penetrant would penetrate the joint or affect fatigue life during service conditions in a corrosive environment. For the joints with a flexible jointing compound the penetrant did not significantly change fatigue characteristics.

The author suggests these observations all can be explained by the effect of penetrant reducing the frictional force. A possible explanation for why the flexible interfay was not affected is that its flexibility already allowed a large amount of load to be taken by the fasteners. He states that Australian investigators came to similar conclusions. Two criteria required for a reduction in fatigue life due to penetrant are presented by the author [103]:

1. The penetrant must get to the faying surfaces.
2. When there is no penetrant, a significant part of the load must be taken by friction.

One investigator found that an interfaying compound was detrimental at high loads but beneficial at low loads [110]. Another found that at a low stress level the penetrant reduced life by 33 percent. At a high stress level the penetrant reduced life by 50 percent [108].

One study showing a penetrant increasing fatigue lives involved Ardrox 985 P3T fluorescent penetrant utilized in non destructive

inspection of aircraft parts [109]. Specimens were clad and unclad 2024-T3 riveted lap joints which were anodized and had an adhesive bonding primer applied before assembly. The fatigue lives of both clad and unclad specimens were improved with the use of a penetrant. The author suspected this may be due to the penetrant preventing oxygen from reaching the crack tip. He examined the fracture surfaces of specimens coated with penetrant fatigued in air. They did not look like specimens which have been fatigued in a vacuum so he assumed a lack of oxygen was not responsible for the increase in fatigue strength [109].

The author suggests that, if a particular joint has fasteners which can easily withstand the increased load due to a reduction in load taken by friction, then penetrants would have a beneficial effect on the fatigue strength. When the penetrant was used, fatigue cracks did not nucleate at fretting scars [109].

Also of interest is the penetrants effect on paints and non-destructive inspection. Although penetrants appear to have an insignificant effect on paints [110], they do have a serious effect on inspection [109]. Dye penetrant inspection methods are affected by penetrants that were previously applied. Attempts to remove the old anti-corrosion penetrants with cleaning fluids were not effective. The difficulty of using ultrasonic detection methods also increases if penetrants are used [110].

At times aerospace fasteners may be installed wet with primer. One study of zinc chromate primer on a lockbolt showed that wet installation slightly decreases fatigue life. This may not be of concern as wet installation is used primarily for corrosion resistance [27].

For 2000 series aluminum alloys the military usually anodizes or alodynes the surface, then applies an epoxy primer, and may apply a polyurethane top coat [27]. This may be a questionable practice from a fatigue point of view as many anodizing processes decrease fatigue life. Another study found that anodizing may have increased the fatigue life of aluminum lap joints. Chromic acid and sulfuric acid methods had similar results. A thin sulfuric acid anodic coating was just as good as a thicker one. Painting the anodized surface did reduce the fatigue life of the joint [102].

4.4 FASTENER MODIFICATIONS FOR FATIGUE.

Many fasteners have been developed which drastically increase fatigue life. One program investigating modifications to fasteners showed a 100 percent improvement in fatigue life [111]. As the unfretted fatigue strength is increased, fretting failures will become more common.

Fastener material can affect fatigue characteristics of a joint by its unfretted fatigue strength and modulus [71]. Studies on aluminum and titanium fasteners have shown that at times the fastener material does not change fatigue life of the joint [112,27].

Clearance fit fasteners have low fatigue lives. When a fastener hole is loaded it tries to become oval, if there is a fastener in place to restrain the deformation, the fatigue life will increase [71]. Rivets that fill holes have better fatigue lives [101]. Interference fits cause tangential tensile stresses and radial compressive stresses. Fatigue lives usually increase with interference fits but increasing interference beyond a maximum level will decrease life [27,71]. Since interference fit fasteners usually have a reamed hole, fatigue lives may also increase from straighter holes and less bending moment [27].

Increased shank contact has been associated with longer fatigue lives [27]. Profiled shanks reduce fatigue strength due to decreased resistance to holes becoming oval and concentrated surface stresses [71].

One study found that the method used to rivet (hydraulic, pneumatic, or by hand) was not significant to fatigue life. It also was found that a large driven head increased fatigue life, probably the result of more load taken by friction [102]. This was true even though rivet installations do not have a lot of residual stress or clamp-up in comparison to other fasteners used in aircraft [101]. When installing rivets the hole can be cold-worked. A study found that the beneficial fatigue effect of cold work was greater than that due to interference [71].

4.5 APPLICATION OF PALLIATIVES TESTED ON AIRCRAFT JOINTS.

4.5.1 Mechanical Methods.

Methods which cold-work have been found to significantly increase the fatigue life of joints [27]. One author found that the fatigue strength of joints improved from 15 to 300 percent. The best results were obtained with cold rolling. This might be because cold rolling produces maximum depth of residual compressive stress [98]. Hole cold working has been found to be about half as effective as installing a fastener with an interference fit. The surface roughness that results from cold working a hole may not influence the fatigue strength. In one study, for the aluminum alloy tested, fatigue strength was found to be nearly completely insensitive to hole roughness [27].

Shot peening is the preferred method of cold working outside of holes because of cost, reproducibility, and availability of equipment and data [98]. Studies on shot-peened joints have shown there is no reduction in fretting damage but fatigue lives increase due to slower crack propagation [56,71].

There are many methods of cold-working holes. A common method is to pull an oversized mandrel through the hole. The hole may be protected by a sleeve or lubrication. This method is very effective when holes are pre-cracked [27]. Roll peening also can be used to produce close tolerance holes but the compressive layer is thin [98].

4.5.2 Shims.

When soft aluminum shims were placed in lap joints, no significant improvement in fatigue was observed. Stainless steel pads were bonded to the aluminum in a lap joint. It was thought the adhesive could absorb some motion. Cracks in the steel could also not propagate through the adhesive to get to the aluminum. Shot peening then bonding on some steel showed the best joint fatigue life, even better than bonding [56].

4.5.3 Materials.

One author suggests that lower strength materials may have better joint fatigue characteristics because they can yield locally and relieve stresses [12]. Grain direction can also be important in joint fatigue

analysis. In one study of a 7075-T6 joint, the ratio of predictions to test results was 1.22 after grain direction effects were taken into account [101].

4.5.4 Lubricants.

Solid lubricants tend to be removed or wiped away. Surfaces which are grit blasted or chemically treated are better at retaining lubrication [112].

Teflon tape has been tested in joints, it was found to allow load transfer to the fastener holes. In another test aluminum was oxidized and impregnated with Teflon. No fatigue improvement was found [56]. Creep and cold flow properties of Teflon are better if it is "ceramic filled Teflon". This material increased life at high cycles [56].

Molybdenum disulphide impregnated nylon in a joint resulted in failure at the fasteners or holes [68,56]. Another study found that using a lubricant to install interference fit fasteners may be beneficial to fatigue [71].

4.5.5 Other Palliatives.

One investigation on fretting fatigue of titanium joints concluded the best treatment against fretting damage is a combination. The titanium should be shot peened, then grit blasted, then have fluoride phosphate or Tiodize II applied, then have some solid film lubricant applied. Both the fluoride-phosphate and Tiodize II coatings did not affect fatigue [112].

5. SUMMARY AND CONCLUSIONS.

In the section on mechanisms, studies on fretting processes and possible mechanisms of crack nucleation were discussed. Adhesion is commonly suggested to be the main cause of crack nucleation during fretting fatigue. The stresses induced by fretting contact may cause nucleated cracks to grow at significantly increased rates or may slow crack growth to the point of effectively preventing further propagation. Stress field calculations have shown that it is possible to predict which nucleated crack will grow to failure. As our interest lies in fretting and fretting fatigue of aircraft joints, possible future work could include the development of stress field calculations for typical aircraft joint geometries. A finite element method would be a necessity given the complexity of the situation. The predictions of such a stress model could then be compared to observed failures in aircraft joints to verify the accuracy of the model.

The section on palliatives for fretting and fretting fatigue showed that a palliative's effect on fretting fatigue is extremely case-specific. A palliative may be reported to considerably reduce fretting fatigue in one situation, while another investigator with a slightly different testing situation can find no benefit or even a reduction in fretting fatigue performance. It was found that the only palliatives which consistently increased fretting fatigue life were based on increasing the unfretted fatigue strength. Methods that induced residual compressive stresses in the surface, such as shot peening, were nearly always of benefit. Possible future research might include the development of a finite element model in which loading, properties of the palliative, and geometry could be modified to represent a specific case. Such a general model would be useful as the details of a fretting contact govern the result of that fretting contact and finite element methods are useful in analyzing these types of details. Such a model could be of benefit as a cost effective method of selecting the best palliative for a given situation with a relatively low cost. It might also be possible to compare fatigue predictions from the stress model with results of laboratory tests given in the literature. This would be a quick way to screen palliatives in an attempt to determine which have significant effects on fretting fatigue that are not a result of the palliative's effect on the macroscopic stress state.

The last section of this report detailed investigations of fretting in aircraft joints. Substantial evidence was found that fretting fatigue could be a pervasive problem with riveted aircraft joints. It was

often observed that many palliatives to reduce fretting fatigue in joints would also lower the ratio of load taken by friction in the joint. This has the effect of increasing the load ratio on the fasteners, and thus decreases their fatigue life. It was often found that the increase in fatigue life due to reduced fretting was overpowered by the reduction in fatigue life at the fasteners. A future study to develop methods of reducing fretting fatigue that would not increase the bearing load on the fastener would be beneficial to the industry. Such an investigation may lead to the development of improved faying surface sealants, fastener designs, or joint designs.

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